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DESIGN AND PERFORMANCE OF THE SLAC RF DRIVE SYSTEM*

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Summary

This paper describes the design and performance of the RF drive system of the Stanford Two-Mile Linear Accelerator. The function of this system is to supply a drive signal of 240 watts to each of the 240-24 MW klystron amplifiers whose power accelerates the beam. The following sub-systems are discussed: A highly stable tunable master oscillator at 476 MHz, a 17.5 kW CW main booster amplifier, a two-mile temperature stabilized 3-1/8 inch diameter main drive line, 30 times-six varactor frequency multipliers, 30 pulse modulators and sub-booster klystrons, 30 temperature stabilized 1-5/8 inch diameter sub-drive lines, isolator-phase shifter-attenuators used before each sub-booster and 24 MW klystron, the phase-stable interconnecting cables, and standby equipment.

System Design

Three basic requirements were originally placed on the RF system for the accelerator:

1. A drive signal of at least 240 watts must be fed to each 24 MW klystron.

2. The RF phase of the drive signal to each of these klystrons must be adjustable so that the traveling RF wave crests in the accelerator and the electron bunches can be made to coincide within ±5°. This phase relationship must be preserved in the presence of daily environmental changes.

3. The phase relationship must be preserved over a tuning range of ±0.1 MHz centered around 2856 MHz.

The minimum drive requirement for each 24 MW klystron was dictated by the need to operate each tube at saturation where output power variations are minimized.

The following considerations led to the ±5° requirement:

The total electron energy V_T is the sum of the individual contributions of the N accelerator sections, i.e.,

$$V_T = \sum_{1}^{N} V_n \cos \theta_n \qquad (1)$$

where V_n is the maximum possible energy gain for a given RF power input and θ_n is the phasing error in section n. For small values of θ_n and equal values of V per section, Eq. (1) may be written

$$V_T \cong VN\left(1 - \frac{1}{2}\overline{\theta^2}\right) \qquad (2)$$

where $\overline{\theta^2}$ is the average value of $\theta_n^{\,2}$. For the accelerator energy to attain 99.5% of its maximum value, it is necessary that $\overline{\theta^2} = 0.01$ or $|\theta| \leq 5°$.

The frequency tuning requirement was derived from the need to track accelerator structure temperature changes with changes in the RF drive frequency. While such tracking is not being used often in Stage I (240 klystrons), it will be necessary in Stage II (960 klystrons). The frequency tuning requirement in turn means that the slope of the phase-frequency characteristic of the main transmission line must be the same as that of an ideal TEM line to avoid rephasing the accelerator whenever the drive frequency is changed.

The system which was built to meet these requirements is the RF Drive System, shown in Figure 1.† That portion of the drive system from the varactor multiplier onward is repeated 30 times along the length of the accelerator. The components in series within each of these parallel paths must exhibit good phase stability with environmental changes in order to minimize loss of beam energy and to avoid constant rephasing of the accelerator. Consequently, major efforts were devoted to measuring and improving the phase stability of all components in the parallel paths.

Other systems were considered before the design shown in Figure 1 was selected. A primary consideration was the main drive line. S-band waveguide was rejected because of high dispersion, high attenuation, and expensive temperature control requirements. L-band guide was considered, including circular configurations, but coupler problems, multi-mode suppression, and temperature control problems caused these approaches to be rejected. An S-band coaxial line system would have solved the dispersion and temperature problems, but the attenuation at 2856 MHz was too high. However, a coaxial line operating at a sub-harmonic of the accelerator frequency offered low attenuation, and the advent of varactor diode

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† The Automatic Phasing System which actually determines the phase of the electron bunches and adjusts the RF phase of each drive signal has been described in an earlier paper[1].

frequency multipliers provided a means of multiplying to the accelerator frequency with a reliable, efficient, and phase stable device. A multiplication factor of 6 resulted in an appropriate compromise between the need for a low frequency for low attenuation in the drive line, and a high frequency for reduced complexity, and hence better phase stability, in the frequency multiplier. In the following sections, the various sub-systems will be discussed in detail.

Master Oscillator

The master oscillator is the starting point of the radio frequency drive system. The output frequency is 476 MHz, the frequency at which distribution of RF along the entire two-mile length of the accelerator takes place. The output power is 8 watts, which, with ample margin for losses, provides at least two watts to both the on-line and standby main booster amplifiers. The oscillator has a tunability of ±16.7 kHz, (±100 kHz at 2856 MHz) and a frequency stability of 1 part in 10^7 per hour. Harmonic and spurious output is at least 60 dB below carrier level, and amplitude stability is better than ±0.5 dB per week. This amplitude stability is necessary to minimize an amplitude to phase conversion in the subsequent frequency multipliers.

Both local and remote frequency tuning is available. A 39.67 MHz output is provided for driving an RF deflector in the beam injection system, and a low level 476 MHz output is provided to phase lock the standby oscillator to the on-line unit, so that instantaneous switching can be accomplished in the event of a master oscillator failure.

A block diagram of the master oscillator is given in Figure 2. The crystal oscillator, and voltage, amplitude and temperature regulator circuits are enclosed in a proportional oven. Frequency tuning is accomplished by applying a well regulated voltage through a motor driven potentiometer to a varactor diode, which slightly alters the frequency of the 39.67 MHz crystal oscillator.

The Main Booster Amplifier

The function of the main booster is to amplify the several watt output of the master oscillator to a level of 17.5 kW at 476 MHz, for delivery to the main drive line.

The output power of 17.5 kW was selected to allow 4.25 watts to be extracted from the main drive line at each of 30 sectors with couplers having no closer coupling than 10 dB and after line losses, permit about 50 watts to be received at the far end of the two-mile main drive line for distribution into the end stations.

The amplifier tube is a UHF TV type klystron having four external cavities.

An unusual feature of the amplifier is the high degree of output power stability: ±0.1 dB per week. The output power stability requirement was dictated by the fact that the varactor frequency multipliers driven by the main booster amplifier show substantial amplitude to phase conversion. Power changes of ±0.1 dB can produce up to ±0.5° phase shift at the frequency multiplier outputs.

A block diagram of the main booster amplifier is given in Figure 3.

Main Drive Line

The main drive line transmits 476 MHz power from the main booster located in the injector area, to the end of the accelerator, and includes 30 equally spaced couplers to feed input power to each of 30 frequency multipliers located at the beginning of each of the 30 sectors that make up the machine. The remaining power, at the end of the main drive line, is transmitted via 1500' of 7/8" Spiroline coaxial line to the end stations. An extra coupler at Sector 28 provides 1 watt for Central Control to monitor power and frequency of the drive signal.

The main drive line consists of slightly over 10,000' of 3-1/8 inch EIA standard copper coaxial line having an attenuation of 0.25 dB per 100'. The required input power is given by

$$P = \sum_{1}^{N} P_n \; r_n \qquad (3)$$

where P_n is the output power at the nth coupler, and r_n is the attenuation of the line to the nth coupler.

When the couplers are equally spaced and deliver equal power, the expression above reduces to:

$$P = \frac{r^N - 1}{r - 1} \qquad (4)$$

In this case r is the attenuation between couplers. This expression led to an input power of 6 kW. However, to provide an additional 50 watts at the end of the main drive line for use in the end stations, and to allow a safety factor, the actual input power was set at 17.5 kW.

Environmental Phase Stability

Environmental factors effect the phase stability of the main drive line in the following ways:

1. The length varies as a function of temperature.

2. The dielectric constant of the gas inside the lines varies due to changes in the temperature to pressure ratio (density) and changes in composition (moisture content).

3. The dielectric constant of the Teflon center conductor supports changes with temperature.

The phase shift of the drive line is:

$$\phi = \sqrt{\epsilon_a}\frac{\ell_a}{c}\omega + \sqrt{\epsilon_t}\frac{\ell_t}{c}\omega \qquad (5)$$

where ϵ_a = dielectric constant of air

ϵ_ϵ = dielectric constant of Teflon center conductor supports

ℓ_a = length of that portion of the line filled with air

ℓ_ϵ = length of that portion of the line filled with Teflon

Defining

$$\sqrt{\epsilon_a} = 1 + \delta_a \text{ and } \sqrt{\epsilon_t} = 1 + \delta_t,$$

then

$$\phi = \frac{\ell + \ell_a\delta_a + \ell_t\delta_t}{c}\omega = \tau\omega \qquad (6)$$

where τ is defined as time delay. The time delay errors at 2856 MHz are readily expressed in terms of phase delay since they are numerically nearly equal (1 picosecond = 1.026°).

To control the length variations, all output ports are rigidly anchored to the concrete floor of the klystron gallery. The line is supported on rollers at ten-foot intervals to avoid excessive stresses, and variations in line length are taken up by expansion sections which allow both inner and outer conductors to slide past each other.

To control the phase shift due to changes in dielectric constant of the gas inside the line the pressure is maintained constant within ±0.01 psi, and the temperature is regulated to within ±1°F. δ_a is given by[2]

$$\delta_a = 105 \times 10^{-6}\frac{P}{T}$$

where P is air pressure in mmHg and T is air temperature in °K. From the expressions above we obtain:

$$\frac{d\tau}{\tau} = \frac{d\ell}{\ell} + \delta_a\left[\frac{dP}{P} - \frac{dT}{T}\right] \qquad (7)$$

$\frac{d\ell}{\ell}$ is found from the expansion coefficient of copper: 9.7×10^{-6}/°F. The relative and absolute changes in time delay for the two-mile line ($\tau = 10^{-5}$ seconds) per unit change in temperature and pressure are given below in Table I.

Phase Frequency Response

Since the coincidence of the RF drive signal wave crest and arrival of the electron bunches must be preserved over a tuning range of ±0.1 MHz, and the maximum alloted phase error is 1°, the restriction imposed on the relative group delay of the drive line is as follows:

Let ϕ_e = total phase shift of the beam

ϕ_w = total phase shift of RF wave

τ_{ge} = group delay of beam (beam length divided by beam velocity)

τ_{gw} = group delay of RF wave

From the definition of group delay we have:

$$\delta\phi_e = \tau_{ge}\delta_\omega, \qquad \delta\phi_w = \tau_{gw}\delta\omega$$

and

$$\delta\phi = \delta\phi_w - \delta\phi_e = \tau_{ge}\left(\frac{\tau_{gw}}{\tau_{ge}} - 1\right)\delta\omega$$

The relative group delay of the drive line is related to the phase error tolerance by:

$$\frac{\tau_{gw}}{\tau_{ge}} = 1 + \frac{\Delta\phi}{360\ \tau\Delta f} \qquad (8)$$

For

$\delta\phi$ = 1° allowable error

$\tau_{ge} = 10^{-5}$ seconds group delay of beam

Δf = ±0.1 MHz

the relative group delay of the wave is constrained to the range 0.997 to 1.003. If the length of the beam and wave travel are identical then this constraint applies to the relative group velocity, $\frac{v_g}{c}$. The relative group velocity of the beam differs from unity by $1/\gamma^2$ where γ is the ratio of total mass to the rest mass of the electron. Thus after the first few feet of acceleration $\tau_{ge} = \frac{L_e}{c}$ where L_e is the total length of the beam. The relative group delay of the wave is effected by the dielectric loading due to inner conductor supports. This slows down the wave, which reduces the group velocity. In addition, the supports present periodic discontinuities along the line. The reflection from the discontinuities may increase or decrease group delay. Of these two effects the larger is dielectric loading. This introduces a maximum delay of in the order of 10 nanoseconds. The latter effect is proportional to the product of the reflection coefficients of individual reflection coefficients that are of the order of 0.05.

Table I

Time Delay as a Function of Air Temperature and Pressure Variations

	760 mmHg, 80°F	760 mmHg, 112°F	1 micron, 80°F
δ_a	266×10^{-6}	252×10^{-6}	0.35×10^{-12}
$\frac{d\tau}{\tau}$	-0.492×10^{-6}/°F	-0.440×10^{-6}/°F	-0.648×10^{-12}/°F
	18.1×10^{-6}/psi	17.15×10^{-6}/psi	0.35×10^{-12}/micron
$\Delta\tau$	-4.92 psec/°F	-4.41 psec/°F	-0.648 psec/°F
	181 psec/psi	17.15 psec/psi	0.35 psec/micron

Sub-Drive Lines

Each of 30 sub-drive lines transmits 60 kW peak power output from the sub-boosters and distributes this power equally to eight 24 MW peak power klystrons. Because the length of each sub-drive line is 1/30 the length of the main drive line, the relative phase frequency response and phase time variation can be relaxed by the same factor. The sub-drive lines are 1-5/8 inch EIA standard copper coaxial line.

Varactor Frequency Multipliers

The frequency multiplier receives 4.25 watts input from the main drive line, multiplies by a factor of 6 to 2856 MHz and generates 400 mW at the output frequency for delivery to the sub-booster klystron.

The phase stability requirement is ±1° per week between outputs of any two multipliers.

A block diagram of the frequency multiplier is given in Figure 4.

Referring to Figure 4, the function of the input attenuator is to adjust the input power to the precise value required for maximum phase stability. The double oven maintains the temperature of the multiplier circuitry at 68°C ±0.1°C. The band pass filter eliminates spurious outputs (mainly 5th and 7th harmonics of the input frequency). A bias supply rather than self-biasing is used for two reasons:

1. Starting problems are reduced by the use of fixed bias;

2. It has been found possible to minimize phase shift as a function of drive power by small adjustments of bias.

Sub-Booster Klystron and Modulator

The sub-booster klystron supplies the sub-drive line with 2856 MHz pulse power to drive the 8 24 MW klystron amplifiers of each 333' sector.

A 60 kW klystron with a gain of 60 dB was developed for this purpose. The tube is water cooled and uses an integral periodic permanent magnet for focusing. The 60 kW output provides sufficient power for Stage II (960 klystrons) with a 9 dB margin for compensate for losses in the RF path to each 24 MW klystron.

In order to satisfy the stringent stability requirements of the RF drive system, it was necessary to design a very high quality modulator. The specification on voltage stability is ±0.04% droop and ripple within a pulse, and ±0.32% drift in a period of one week. Since it was quite difficult to make direct voltage measurements on the modulator, a measurement was made of the phase shift across the sub-booster klystron, using a highly stable bridge and the measured phase shifts were then related mathematically to voltage variations in the modulator.

Isolator - Phase Shifter - Attenuator Units

The function of the Isolator-Phase Shifter-Attenuator (IØA) unit is to control the amplitude and phase of the drive signals reaching each sub-booster klystron and each 24 MW klystron.

The unit consists of the following components:

1. A level-set attenuator, 0 to 25 dB

2. A protection attenuator, 0 to 25 dB

3. A phase shifter

4. A 30 dB isolator.

With the level-set attenuator the drive level is adjusted for saturation of the klystron. The protection attenuator prevents sudden application of RF power to the klystron window. It has been found that slow application of RF drive greatly reduces the rate of window failure. The 30 dB isolator was incorporated in the IØA unit to prevent mismatch at the output of the IØA unit from causing phase errors at other sub-drive line couplers, and to isolate the phase shifter.

The four components listed above, and the necessary motor drives were placed together in a compact unit. The sub-booster IØA units are installed in the sub-booster modulator cabinet. The 24 MW IØA units are installed in a rack adjacent to each 24 MW klystron.

Dropout Cables

The dropout cables are used to connect all the units and systems together: The main drive line to the varactor multipliers, the varactor multipliers to the sub-booster IØA, the sub-booster IØA to the sub-booster klystron, the sub-drive line to the 24 MW klystron IØA and the IØA to the 24 MW klystron. The dropout cables are a foam dielectric semi-flexible coaxial line having a phase stability of ±0.60 electrical degrees per foot from 60°F to 100°F, and ±0.91 electrical degrees per foot from 100°F to 130°F.

Standby Equipment

To improve the reliability of the RF drive system, several items of equipment are backed up by standby equipment. One operating spare is available at all times for the master oscillator, the main booster amplifier and the sub-booster modulator of Sector 1. For this equipment automatic switching is provided in the event of failure. Manual switching can also be performed, either from Central Control Room, or locally at the master oscillator rack in Sector 1.

Performance

The master oscillators have operated satisfactorily with virtually no maintenance over a period of two years.

Main booster and sub-booster klystron life has been well in excess of guaranteed life. Sub-booster modulator switch tubes have been a problem, but an improved tube has resulted in longer life.

Long term phase stability measurements on a 2000' length of main drive line, with the results extrapolated to the entire length indicate less than 7° phase shift in 60 hours. Group delay measurements, extrapolated in a similar manner, gave a value of 0.9975.

The operation of the varactor diodes has been extremely stable except that on one occasion the main booster regulator system failed, 25 kW was delivered to the main drive line, and 12 diodes failed simultaneously.

The accelerator has been operated at constant energy levels without rephasing for periods of as long as forty hours, showing that the drive system as a whole is performing according to specifications.

Acknowledgements

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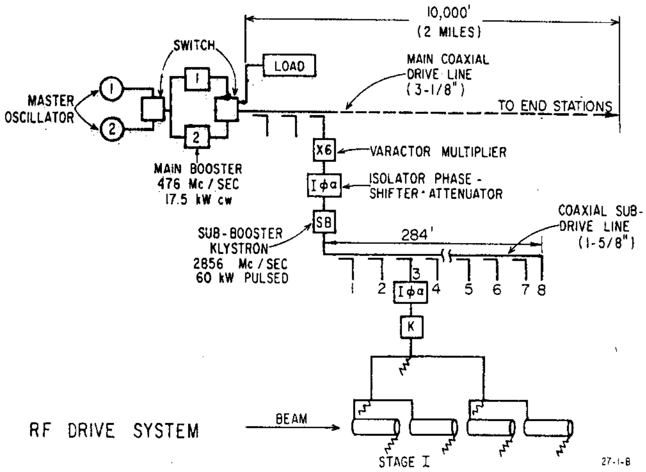

Fig. 1. RF Drive System.

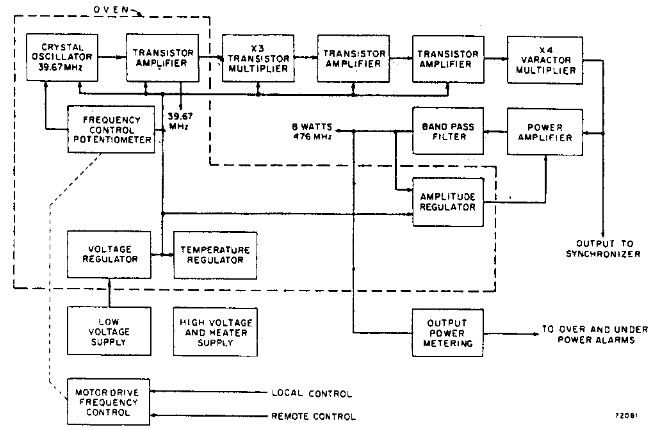

Fig. 2. Master Oscillator.

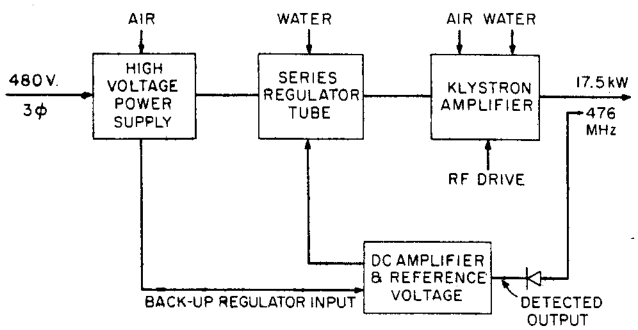

Fig. 3. Main Booster Amplifier.

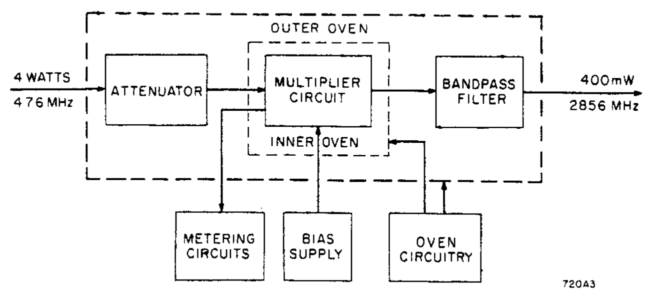

Fig. 4. Frequency Multiplier.